



## **Recurrence of Extreme Coastal Erosion in SE Australia Beyond Historical Timescales Inferred From Beach Ridge Morphostratigraphy**

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# Geophysical Research Letters



## RESEARCH LETTER

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### Key Points:

- Short observational history in SE Australia hinders assessment of whether extreme beach retreat in the 1970s is an isolated or recurrent event
- High-precision morphostratigraphic analysis of beach ridge evolution augments 40 years of beach profiling at Moruya in NSW
- Extreme beach retreat is found to have occurred around 1650–1700, revealing that the 1970s event is a recurrent phenomenon

### Supporting Information:

- Supporting Information S1
- Table S1
- Table S2

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## Recurrence of Extreme Coastal Erosion in SE Australia Beyond Historical Timescales Inferred From Beach Ridge Morphostratigraphy

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**Abstract** Extreme storms present a major risk to coasts. Increasing populations worldwide, together with sea level rise, exacerbate concerns for coastal settlements, but the low frequency of extreme storms makes an assessment of risk difficult. In southeast Australia, the severest beach retreat on record relates to a series of extratropical cyclones in the 1970s, but the relatively short observational record hinders assessment of how frequent these events are. At Moruya in New South Wales, four decades of beach monitoring has provided new insights into response of beaches to extreme storms. We augment this recorded history with morphostratigraphic analysis of beach ridge evolution by using ground-penetrating radar and optically stimulated luminescence dating. We find an episode of extreme retreat over 550 years, proving that the 1970s extreme event is a recurrent phenomenon. Our high-precision morphostratigraphic analysis provides evidence with which to better plan coastal adaptation.

## 1. Introduction

Coastal storms are associated with large waves and storm surges, causing damage to property and infrastructure (Goslin & Clemmensen, 2017; Masselink & van Heteren, 2014). Such risks must be assessed for individual coastlines (Wainwright et al., 2015); however, it is not clear whether observations of beach processes spanning several decades are adequate for understanding and predicting recurrence of infrequent extraordinary events. This is a substantial knowledge gap in view of projected future sea level rise and possible intensification of storms due to climate change (Ashton et al., 2008; Ranasinghe, 2016).

A series of extratropical cyclones between 24 May and 16 June 1974 resulted in the most severe beach erosion that has been observed along the New South Wales (NSW) coastline, inflicting significant damage (Bryant & Kidd, 1975; Foster et al., 1975). The first of these, named the Sygna storm, after a 53,000-t Norwegian bulk carrier shipwrecked during the event, was the most intense event recorded by beach profiling data in Australia's history. The 1974 event was followed by several storms culminating in 1978 (McLean & Shen, 2006; Thom & Hall, 1991). These storms alerted the NSW government to the need for increased understanding of coastal processes, prompting widespread monitoring of wave conditions along this coastline (Lord & Kulmar, 2001). A beach monitoring program began fortuitously in 1972 at Bengello Beach near Moruya, in southern NSW (McLean et al., 2010; McLean & Shen, 2006; Thom & Hall, 1991), and is to our knowledge one of the longest continuous programs in the world. Beach monitoring demonstrates that the 1974 storm event eroded 100 m<sup>3</sup>/m of sand and that all subsequent storms caused smaller retreats (up to 70 m<sup>3</sup>/m; McLean et al., 2010); after 1978, the beach started to recover and returned to its previous state by 1983 (Thom & Hall, 1991). The 1974 retreat was considered by coastal managers to have a recurrence of approximately 100 years. Wave monitoring along the coast implies that wave conditions during the Sygna storm have a return period of about 50 years, but it was the coincidence with the highest water level ever recorded by the tide gauge in Sydney (1.46 m above mean sea level on 25 May 1974) that made coastal damage so severe (Lord & Kulmar, 2001). Despite being labeled as the 1-in-100-year storm for this coastline, the frequency of an event of this magnitude has not been empirically demonstrated

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being beyond the timescale of current observational data in Australia. Given increases in population along potentially vulnerable stretches of coastline since 1974, establishing recurrence intervals of such events is imperative for informed coastal management.

Geomorphological archives have often been utilized for assessing infrequent, devastating coastal events, such as hurricanes (Donnelly & Woodruff, 2007; Mann et al., 2009) and tsunamis (Dawson & Stewart, 2007; Nanayama et al., 2003; Sawai et al., 2015). Reconstruction of coastal events is not only useful for determining recurrence intervals but may also provide other quantitative data such as inundation distance and earthquake magnitude (Nanayama et al., 2003; Sawai et al., 2012). Occurrences of past storm erosion is also detectable from stratigraphic characterization of beach scarps (Buynevich et al., 2007; Tamura, 2012). However, assessment of the magnitude of retreat during erosional events is needed. This is problematic because shoreline position prior to erosion events is not preserved.

This paper presents an integrated morphostratigraphic analysis to investigate the magnitude of past beach erosion. The >45-year beach monitoring at Bengello Beach was both directly and analogously compared with longer-term beach changes revealed by ground-penetrating radar (GPR) and optically stimulated luminescence (OSL) dating. This comparison established the morphostratigraphic signature of extreme beach retreat observed during the 1974–1978 storms, enabling evidence for earlier events comparable with the 1970s to be sought.

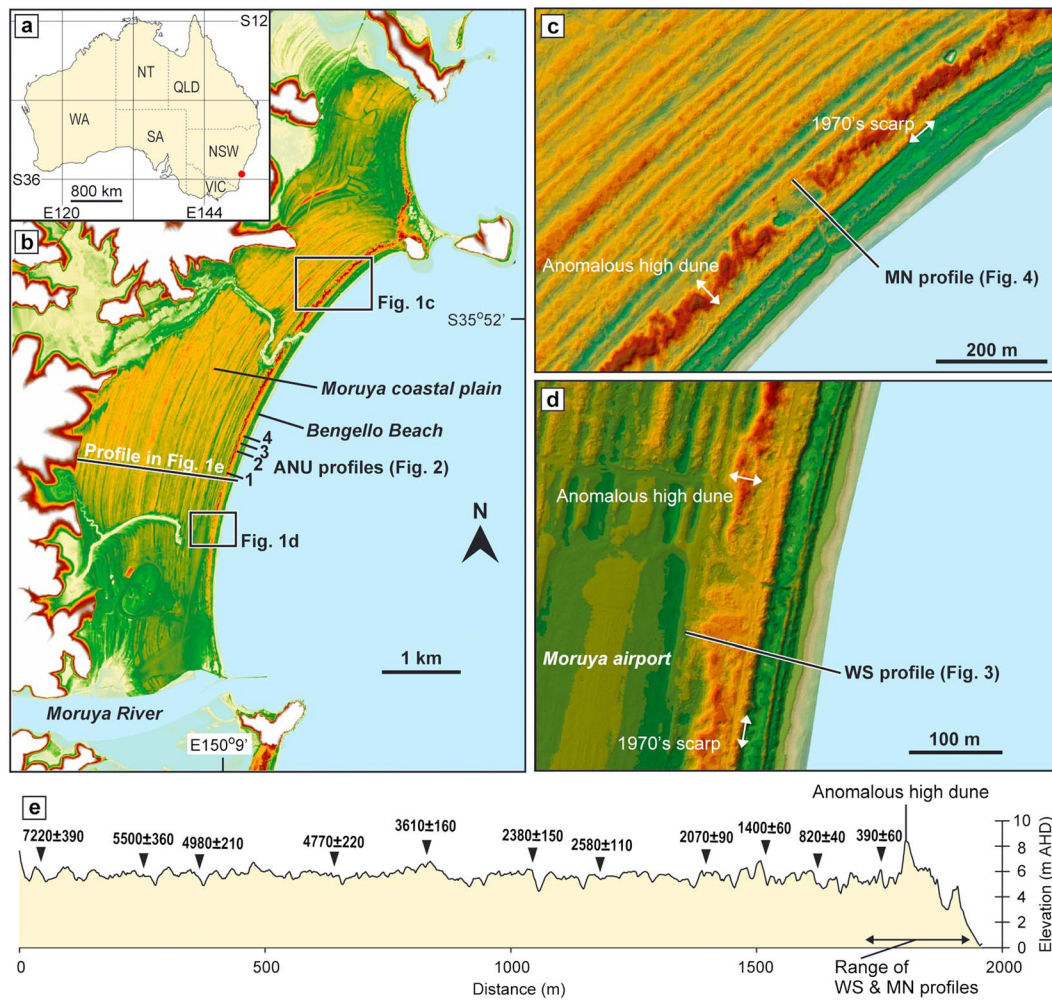
## 2. Study Area

Bengello Beach is a 6-km-long arcuate sandy beach on the Tasman Sea (Figure 1). Along this beach, tides are semidiurnal and microtidal, and wave energy levels are moderate to high, with a mean height of 1.6 m and mean period of 10–12 s (McLean & Shen, 2006). Four shore-perpendicular transects (Thom & Hall, 1991; McLean & Shen, 2006; Figure 1b; No. 1 and 4 profiles are shown in Figure 2b) have been selected for beach monitoring. Sand volume changes ( $\text{m}^3/\text{m}$ ) above mean sea level (Australian Height Datum [AHD]; Shen, 2002; Figure 2a) calculated from these four profiles document the extensive coastal retreat in 1974 and the subsequent erosion-dominated period until 1978 (Thom & Hall, 1991; Figure 2a). The beach profile then recovered during 1978–1983, and the beach profile envelope shifted abruptly seaward (Figure 2c). The beach has then gradually accreted with events of smaller erosion and recovery (McLean & Shen, 2006). Between 1973 and 2008, the average rate of net sand accretion per unit length of shoreline was  $1.55 \text{ m}^3/\text{year}$  (see dashed line in Figure 2a). This is equivalent to the shoreline progradation rate of 0.28 m/year, if divided by 5.6 m, an average elevation of the Moruya beach ridge plain (Figures 1b and 1e). The plain is characterized by the development of about 60 beach ridges, of which OSL ages indicate progradation at a net average rate of 0.27 m/year in relation to the sea level stillstand since 7,200 years ago (Oliver et al., 2015). There is thus good agreement about net accretion rate on multidecadal and millennial time scales.

## 3. Methods

Field surveys were carried out in April (12–14) 2016 and January (12–14) 2017 on the Moruya coastal plain. Two shore-normal transects, WS and MN, were chosen as representative of southern and northern parts of Bengello Beach respectively, extending 150 and 190 m from the shore at the time of survey. Along these transects GPR was used to characterize subsurface sedimentary structures. Sand samples for OSL dating were collected from auger holes at 13 and 7 sites along transects WS and MN, respectively, by hammering light-impenetrable steel tubes into the bottom of holes. Topographic measurements were also made by real-time kinematics global positioning system along the WS transect and by an automatic level referenced to Airborne LiDAR elevations along the MN transect. Elevations are expressed relative to AHD.

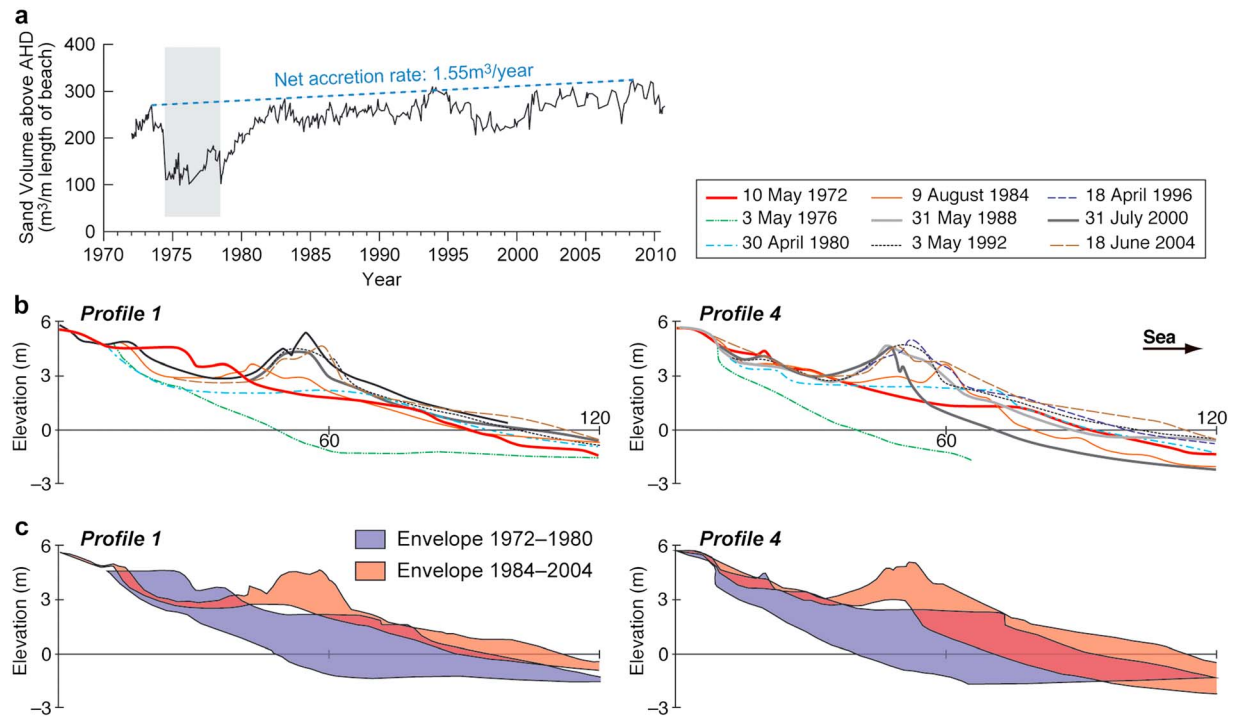
GPR profiles were collected with common offset surveys. A Mala ProEx system (Guideline Geo Inc., Sundbyberg, Sweden) was used with a 250-MHz antenna. Radar wave velocity was set 0.14 and 0.07 m/ns above and below the water table, respectively, informed by the depth to the water table determined with a hand auger. Processing of GPR data was completed in RadExplorer 1.42 and included dewow, first-arrival time correction, automatic gain control, band-pass filtering, and Stolt *F-K* migration. Static correction was also applied to reflect the measured topography assuming radar wave velocity above the water table.



**Figure 1.** (a) Location of study area, southern New South Wales (NSW; shown by a red dot). (b) Airborne LiDAR-based digital elevation map of the Moruya coastal plain. No. 1–4 ANU monitoring profiles are located south of the center of Bengello Beach. The Moruya coastal plain has ~60 beach ridges documenting shoreline progradation driven by nearshore sand supply. Remarkably high dunes are developed alongshore between 100 and 150 m inland of the present shoreline. No such dunes of similar height are evident further inland. Airborne LiDAR data were collected in 2011 by NSW State Government Land and Property Information. This data set was processed to produce a seamless terrestrial “bare Earth” digital elevation model mosaic up to elevations of +20 m above mean sea level with a final raster grid of 1-m resolution (Quadros & Rigby, 2010) using ArcGIS (v. 10.2). (c) A close-up view of the elevation map showing the northern portion Bengello Beach. The MN profile is located where sands of the anomalously high dunes were artificially removed for a car park. (d) A close-up view of the southern Bengello Beach. The WS profile is located along a leveled beach access path just seaward of the Moruya airport. (e) Topographic profile across the entire Moruya coastal plain. Optically stimulated luminescence ages (expressed in years before present) of samples taken from the foredune deposits reveal the coastal progradation over the last 7,000 years (Oliver et al., 2015). AHD = Australian Height Datum.

OSL dating was carried out at the Geological Survey of Japan; details are described in the supporting information (Bateman & Catt, 1996; Cunningham et al., 2011). Quartz grains of 180–250  $\mu\text{m}$  in diameter were extracted through chemical treatments, mesh sieving, and heavy-liquid density separation. Grains were mounted on a stainless-steel disc for the measurements with a TL-DA-20 Risø TL/OSL reader. The equivalent dose ( $D_e$ ) was determined by the single-aliquot regenerative-dose protocol (Murray & Wintle, 2000). Dose recovery, preheat plateau, and thermally transferred OSL tests indicated 180  $^{\circ}\text{C}$  was an optimal preheat temperature for all samples. A cutheat was set at 160  $^{\circ}\text{C}$ . The environmental dose rate was determined considering contributions of radionuclides in sediments and cosmic rays. Concentrations of potassium, uranium, thorium, and rubidium were quantified by inductively coupled plasma mass spectrometry and converted to dose rate (Table S1; Adamiec & Aitken, 1998; Marsh et al., 2002). Cosmic dose rates were calculated according to Prescott and Hutton (1994). An internal dose rate contribution of  $0.03 \pm 0.01$  Gy/ka was also incorporated for the environmental dose (Bowler et al., 2003). Ages were calculated using the “central”





**Figure 2.** (a) Beach volume change observed along ANU profiles since 1972 (McLean et al., 2010; Shen, 2002). The shaded box shows the erosion-dominated period in 1974–1978. The blue dashed line indicates the trend of the net sand accretion to the beach at a rate of  $1.55 \text{ m}^3/\text{year}$ , equivalent to  $0.28 \text{ m}/\text{year}$  progradation assuming the sediment thickness  $5.6 \text{ m}$ , the average elevation of the Moruya coastal plain. (b) Beach profiles of 12 selected timings from 1972 to 2004 on ANU No. 1 and 4 transects (McLean & Shen, 2006). Profiles in 1972, 1976, and 1980 show the beach retreat and subsequent recovery related to the 1970s event, followed by the discrete foredune building. (c) Beach profile envelopes defined by a number of profiles observed for periods 1972–1980 and 1984–2004 along Nos. 1 and 4 transects (McLean & Shen, 2006; Thom & Hall, 1991). The beach envelope shifted seaward abruptly after the beach recovery from 1978. After 1984, no significant beach erosion occurred; the approximate width of the envelope 1984–2004 at  $+2.5 \text{ m}$  Australian Height Datum (AHD) is  $10$  and  $20 \text{ m}$  on No. 1 and 4 profiles, respectively.

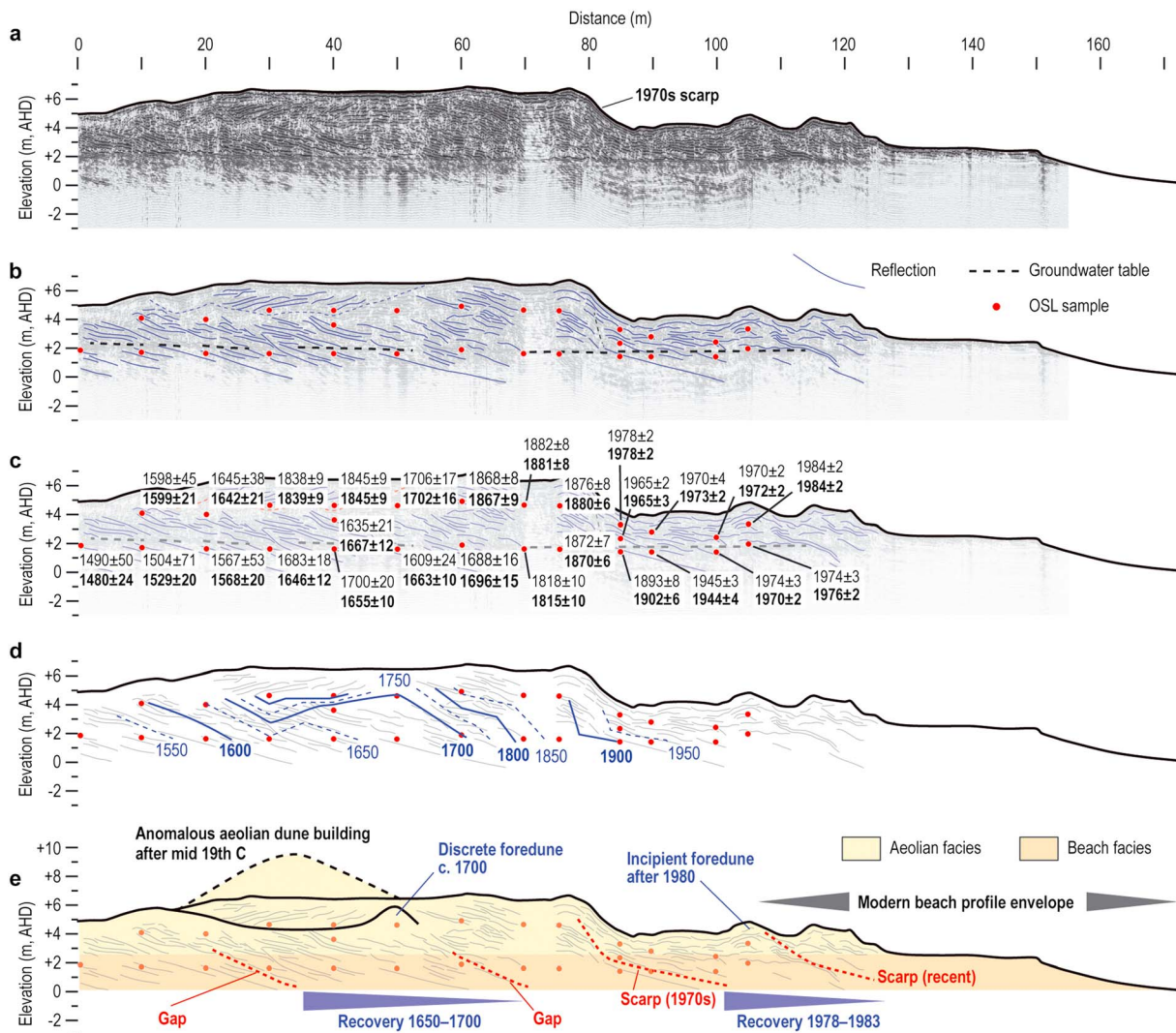
dose (Galbraith et al., 1999) divided by the environmental dose rate or using an integrated, two-dimensional Bayesian chronological model (for details, see the supporting information; Tamura et al., 2019). All ages are determined relative to AD 2016 (Table S2) and then converted to calendar years (AD).

## 4. Results

### 4.1. Topography and GPR Stratigraphy

Airborne LiDAR elevation maps show topographic features of the 1970s beach scarp and anomalous high dunes behind Bengello Beach (Figures 1b–1d). Elevation of the Moruya coastal plain ranges from  $+6.8 \text{ m}$  AHD on ridge crests to  $+4.3 \text{ m}$  AHD in interridge swales. In contrast, an anomalously high dune up to  $+10 \text{ m}$  AHD is laterally continuous alongshore and is  $100$ – $150 \text{ m}$  inland of the present shoreline. Immediately seaward of the high dune, the coastal plain exhibits several more ridges before the abrupt transition to the 1970s relict scarp, where elevation drops to  $+3 \text{ m}$  AHD. A  $30$ - to  $40\text{-m}$ -wide backshore swale lies between the scarp and nearshore incipient foredune approximately  $+5 \text{ m}$  AHD high. The shore-normal transects WS and MN (Figures 1c and 1d) traverse the full width of the high dune at distances of  $10$ – $60$  and  $20$ – $70 \text{ m}$  from their landward ends, respectively (Figures 3a and 4a). We selected transects at sites where the overlying dunes had been lowered to enable beach access and car parking, making it easier for GPR penetration and augering to beach deposits (Figures 1c and 1d). The 1970s scarp is found on transects WS and MN at  $80$  and  $100 \text{ m}$ , respectively.

GPR reflections in the shallow ( $<10 \text{ m}$ ) subsurface stratigraphy of transects WS and MN are generally concave up and seaward dipping, indicating that the majority of the subsurface deposits were formed by seaward accretion of the beach and backshore during shoreline progradation, as in other beach ridge plains (Bristow & Pucillo, 2005; Costas et al., 2016; Oliver et al., 2017; Tamura et al., 2018). The boundary between the beach

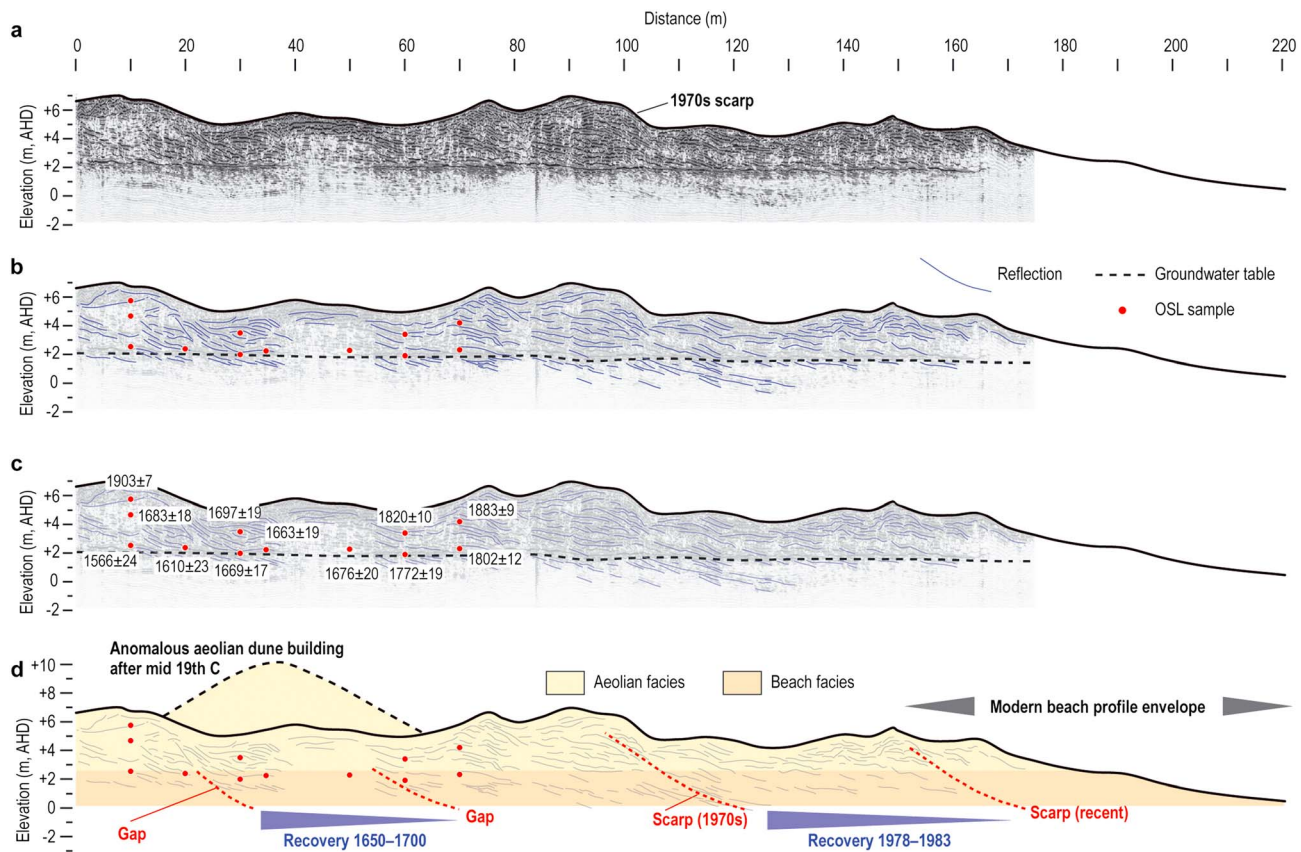


**Figure 3.** (a) Uninterpreted ground-penetrating radar (GPR) profile along the WS transect (Tamura et al., 2019). (b) Line drawing of reflection on the WS profile. Reflections generally dip seaward, revealing the overall seaward coastal progradation. A series of landward dipping reflections at 20–45 m indicate the landward cascading of aeolian sand. (c) Individual (top) and modeled (bottom, in bold) optically stimulated luminescence (OSL) age estimates of sand samples. Ages are expressed in calendar years (AD). Individual ages define a consistent sequence with the GPR stratigraphy, except for five samples at an interval of 30–60 m, which are modified for modeled ages based on Bayesian statistics. (d) Isochrones of every 50 years since 1550 defined by the internally consistent age sequence generated from the Bayesian modeling. A rapid beach progradation is shown for a period 1650–1700, followed by the building of discrete foredune at 50 m. (e) Interpretation of the profile based on the integration of GPR and OSL ages. Gaps in OSL ages of foreshore deposits are accounted for by beach scarps generated from storm erosion. Two rapid beach accretion episodes are defined for 1650–1700 and 1978–1983 that represent beach recovery after extreme coastal erosion. Although artificially leveled, the anomalous high dune is located around the interval of 20–50 m, and the base of this feature is preserved as indicated by the landward dipping reflections and the two OSL ages around 1840–1850. AHD = Australian Height Datum.

and aeolian facies was defined at approximately +2.5 m AHD after the zonation of the present beach, as it was not represented clearly by the GPR profile. Sea level change over the last 500 years along the NSW coast is considered to be very minor (Lewis et al., 2013). At 20–45 m on the WS profile, a series of reflections in the aeolian facies exceptionally dip landward.

#### 4.2. OSL Chronology

OSL ages were determined for 27 and 12 samples from the WS and MN profiles, respectively (Figures 3b and 4b). Constant reworking of sand grains in beach and dune environments generally results in a high degree of bleaching by sunlight, enabling minimum obtainable ages as low as a few decades (Ballarini et al., 2003). Samples collected around the 1970s scarp on the WS profile gave mostly accurate age estimates, an

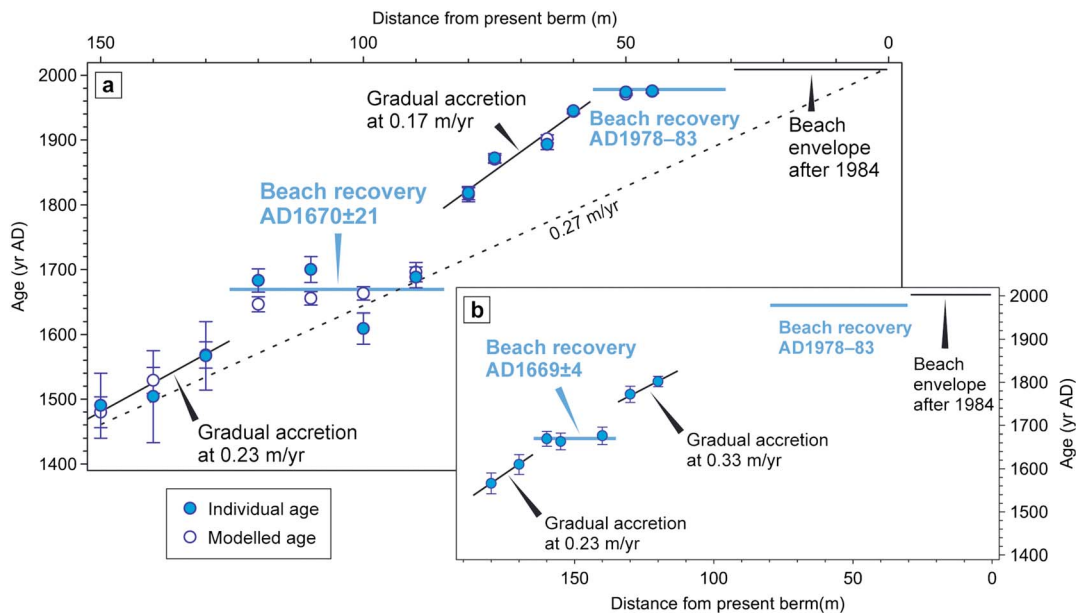


**Figure 4.** (a) Uninterpreted ground-penetrating radar (GPR) profile along the MN transect. (b) Line drawing of reflections on the MN profile. No pronounced reflection corresponds to the 1970s scarp at 100 m. (c) Individual optically stimulated luminescence (OSL) age estimates of sand samples. Bayesian-based modeling was not carried out as there is no age reversal in the individual estimate. (d) Interpretation of the profile based on the integration of GPR and OSL ages. Gaps in OSL ages of foreshore deposits are accounted for by beach scarps generated from storm erosion. Two rapid beach accretion episodes are defined concurrently with the WS profile for 1650–1700 and 1978–1983 that represent the beach recovery after extreme coastal erosion. The anomalous high dunes around the interval of 10–60 m were leveled recently. AHD = Australian Height Datum.

exception being the middle sample at 85 m, immediately above the scarp, that showed an overestimate of 10 years. Small age overestimates (in absolute terms) are often found with very young OSL ages due to incomplete bleaching of OSL signals by sunlight and/or thermally transferred OSL signals (e.g., Madsen & Murray, 2009) and can be identified in a few samples within the No. 1 ANU (The Australian National University) profile (Figure 1b); other samples from the profile gave OSL ages consistent with beach topography changes since 1972 (Tamura et al., 2019).

Individual estimates of OSL ages along the WS profile document the coastal stratigraphic evolution recording incremental progradation over the last 550 years; the oldest age determined for the stratigraphically lowest sample was  $AD\ 1490 \pm 50$  (Figure 3b). Both beach and aeolian deposits were generally younger seaward. Two ages from the aeolian unit exhibiting landward accretion were distinctively younger than both underlying and seaward samples, indicating the occurrence of wind-blown dune sand accreting landward around 1840–1850. Age reversals are recognized in beach deposits at 40–50 m and aeolian deposits at 40 m. These apparent age reversals are caused by random errors in the measurement of the equivalent dose and dose rate, which can result in seemingly inverted ages when the sampling resolution is high. Modeling of the age estimates using Bayesian computational methods provided an internally consistent age sequence with no reversals (Figure 3b; Tamura et al., 2019). Modeled ages from beach deposits in 30–60 m are within a narrow range from  $1646 \pm 12$  to  $1696 \pm 15$ , while their individual estimates have greater data scatter and age reversals. Ages of this interval are thus considered to be almost identical and expected to have a mean age of  $1670 \pm 21$ . The internally consistent sequence of modeled ages allows for defined isochrones every 50 years on the WS profile (Figure 3c). These isochrones reveal rapid accretion around 1650–1700 and the subsequent





**Figure 5.** (a) Plots of depositional ages of beach deposits along the WS profile against distance from the present shoreline as defined at +2.5 m Australian Height Datum. Phases of rapid beach recovery accretion and intervening gradual accretion are recognized. The interval of 0–30 m from the present shore is a zone of present beach envelope, and its age is close to the present. The dashed line indicates the net accretion rate of the southern part of the Bengello Beach, and its comparison with actual trends of depositional ages highlights the sporadic and inconsistent nature of the beach accretion. Mean of the optically stimulated luminescence (OSL) age cluster for the rapid beach recovery in 1650–1700 is an arithmetic average of the four ages associated with the standard deviation. The regression lines for gradual phases are drawn based on the least square of selected OSL ages. (b) Plots defined as in (a) for the MN profile. A beach recovery phase corresponding to the one identified on the WS profile is also defined by a cluster of OSL ages with a mean of  $1669 \pm 4$ .

building of a discrete foredune at 50 m. The swale left behind this discrete foredune was then filled with aeolian sand around 1840–1850 probably in relation to building of the high foredune.

Beach deposits were accreted exclusively seaward, but the accretion rate was inconsistent. Plots of beach depositional ages against distance from the present shore (Figure 5a) show phases of rapid progradation around 1650–1700 (or  $1670 \pm 21$ ) and 1978–1983 (Figure 2c; McLean & Shen, 2006). These phases show much higher rates than the net rate over the past 7,000 and 40 years (Figures 1e and 2a; McLean et al., 2010; Oliver et al., 2015), while intervening phases appear to have rates closer to the net rate (Figure 5a).

OSL ages along the MN profile are stratigraphically consistent with seaward progradation but lie within a narrower age range (AD 1566–1802) than the WS sequence. In particular, three almost identical beach ages at 30–50 m form a cluster at AD  $1669 \pm 4$ , corresponding to the rapid progradation phase identified on the WS profile. A few OSL ages also appear to characterize intervening phases of gradual beach progradation. Although no OSL age was determined, the 1970s scarp is present on the MN profile, indicating that two rapid beach accretion phases in 1650–1700 and 1978–1983 have been preserved in both northern and southern parts of Bengello Beach.

## 5. Discussion and Conclusions

Our morphostratigraphic analysis, combined with >45 years of beach topography measurements (McLean et al., 2010), reveals sporadic progradation of Bengello Beach. The rapid beach recovery around 1650–1700 was associated with much higher accretion rates than the net rate and followed by building of a discrete foredune at circa 1700 (50 m in Figure 3e). These features were also observed after the 1970s erosion, where the sand eroded during the storm was transported back onshore in response to subsequent prolonged fair-weather conditions, forming a new foredune after 1984 (Figure 2c; Thom & Hall, 1991; McLean & Shen, 2006). Based on the similarities, we interpret the recovery around 1650–1700 to represent a similar event as the 1970s erosion. Gaps in individual and/or modeled OSL ages between 20 and 30 m on the WS and MN profiles are thus considered to represent the beach scarp resulting from the erosion prior to the rapid recovery inferred between 1650 and 1700. These gaps in the OSL ages do not necessarily correspond



directly to prominent GPR reflections in all cases, which generally result from higher concentrations of heavy minerals or coarser-grained sediments (Buynevich et al., 2007; Dougherty, 2014; Dougherty et al., 2018; Tamura, 2012). For instance, in the WS profile no heavy-mineral layer was observed during augering around the 1970s scarp despite knowledge of its exact position. In this case, correctly interpreting the pronounced GPR reflections at WS and MN required the ground-truthing and accompanying detailed chronological data that are here presented.

Timing of the inferred beach erosion is considered to be indistinguishable from that of the subsequent beach recovery in 1650–1700, considering that the beach recovered within 10 years after the 1970s event (Thom & Hall, 1991). The preserved depositional unit showing the rapid beach recovery was then bounded seaward by a gap in depositional age > 100 years. Following beach recovery, there must have been continued deposition over the next 100 years, but as this 100-year gap attests, its sediment record was completely lost by a subsequent phase of storm erosion. It is possible that this second storm even eroded part of the beach recovery unit in 1650–1700; the recovery unit after the 1970s erosion was partly reworked by subsequent storms (Figure 2).

The magnitude of beach retreat in 1650–1700 is given by the distance from the shoreline position prior to the erosion and resultant beach scarp. While there is no trace of the shoreline prior to the 1650–1700 event, the beach monitoring records surrounding the 1970s events show that shoreline returned to its preerosion position within 10 years, with a new beach profile envelope established (Figure 2c). The magnitude of the extreme beach retreat,  $d_{\text{ret}}$ , is thus estimated as

$$d_{\text{ret}} = d_{\text{rec}} + d_{\text{env}} - r_{\text{acc}}t,$$

wherein  $d_{\text{rec}}$  is the width of preserved deposits representing postretreat beach recovery and  $d_{\text{env}}$  is the width of beach profile envelope established after the recovery.  $r_{\text{acc}}$  is the rate of net beach progradation, approximately 0.27 m/year for the southern part of the Bengello Beach (Figures 1e and 2a; Oliver et al., 2015), and  $t$  is the time taken for beach recovery, estimated to be no more than 10 years according to the 1970s event. In the case of the 1650–1700 event on the WS profile,  $d_{\text{rec}}$  is approximately 40 m (Figures 3d and 5a) and  $d_{\text{env}}$  is assumed to be 15 m after ANU profiles (Figure 2c).  $d_{\text{ret}}$  is then estimated as approximately 50 m, comparable to that for the 1970s retreat. Here as  $d_{\text{rec}}$  only represents a preserved portion of beach recovery after possible subsequent storm erosion,  $d_{\text{ret}}$  is a conservative estimate. For MN profile,  $d_{\text{rec}}$  is 30 m and  $d_{\text{ret}}$  is estimated to be approximately 40 m, still much larger than any of storm events after 1983 (McLean et al., 2010), in spite of the conservative assumptions.

We conclude that the extreme beach retreat in SE Australia as in 1970s is not a one-off event and happened at least once around 1650–1700, prior to European settlement. So far, there appears to be roughly a 300-year interval, but it is unclear whether more such events happened within that interval. The timing of the event responsible for truncating the beach recovery in 1650–1700 can be presumed identical to the ages of deposits emplaced immediately seaward (Buynevich et al., 2007) and is dated  $1818 \pm 10$  and  $1772 \pm 19$  in the WS and MN profiles, respectively; these ages are several decades apart and probably date two different events. This scarp represents the maximum setback of the shoreline after 1700, which is thus considered to be significant erosion. However, in contrast to the 1650–1700 event, there is no sediment unit representing  $d_{\text{rec}}$ , and thus, the magnitude of retreat cannot be estimated. Successive occurrences of extreme storm events could have eroded the majority of the beach recovery deposits of the former events. The lack of preserved recovery could indicate unfavorable conditions for beach accretion during this time and temporary negative budget of beach sand and/or erosion during subsequent storms. Massive landward accretion of aeolian sand occurred in the midnineteenth century (Figures 3d and 4c), which resulted in the anomalous high dune contrasting with all ridge heights deposited throughout the 7000-year history of the Moruya coastal plain (Figure 1b; Oliver et al., 2015). This phase of aeolian sand building could have consumed sand that might otherwise have produced further shoreline progradation. This suggests that the period between 1700 and 1970s scarp, considered as a gradual phase of beach progradation, could be a result of several episodes of significant beach erosion and subsequent recovery. Our analysis does not guarantee the absence of further such episodes. Thus, recurrence of extreme beach retreat with less than a few hundred years interval should be taken into account for coastal planning in the region. Morphostratigraphic analysis as we did here can be applied to other coastal compartments and is expected to improve our understanding of the long- to middle-term coastal dynamics that are fundamental for sustainable development of coastal areas.

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